Semi-Solid Metal Casting: Reducing the Cost of Copper Alloy Parts

OTA Technology Fact Sheet

What is Semi-Solid Metal Casting?

Semi-solid metal casting (SSM), or die casting with metal in the semi-solid state, is a near-net shape manufacturing method that offers manufacturers and users of copper alloy parts an alternative and, in many cases, lower cost way to produce large quantities of parts with improved part quality compared to traditional pressure die casting. The ability to apply SSM casting to copper alloys is a direct result of the successful development of a high temperature nickel-base alloy die system that significantly extends die life in die casting metals and alloys with high melting temperatures. Since it generally uses widely available cold chamber horizontal die casting machines as the casting unit, SSM casting has the potential for widespread use and application by existing casters equipped with such machines.

SSM casting is done with metal at a temperature between the liquidus and solidus temperatures, with the fraction solid being in the approximate range of 30 to 65%. The semi-solid billet (Figure 1) maintains its shape and is convenient for loading into the shot sleeve of a conventional die casting machine. For the semi-solid metal to have sufficiently low viscosity, the structure at the forming temperature must consist of a globular primary solid phase surrounded by the liquid phase. The technical and economical feasibility of the SSM process are determined, to a large extent, by the approach used to produce the starting stock with the essential precursor structure.

Figure 1: A 3-inch diameter aluminum alloy semi-solid billet being sliced by a knife at 50% solid - 50% liquid. This SSM material has the consistency of modeling clay.

Benefits of SSM Casting

As an innovative casting process, SSM casting offers great potential to save costs, energy, and material, and to reduce the environmental impact of casting. The benefits are:

- Net or near-net shape processing.
- Less thermal fatigue heat, less mold or die wear, and less solidification shrinkage due to the reduced temperature of the feedstock.
- Potential for improved tolerance control due to the inherently tight process temperature control associated with SSM casting and reduced thermal cycling of dies.
- Control of viscosity that can result in less turbulent mold and die filling, which minimizes gas entrainment, porosity, shrinkage, hot tearing, and other solidification defects.
- Lower shear strengths of semi-solid slurries that are associated with lower forming forces than corresponding operations for solid metal, e.g., forging.
- Finer, more uniform, microstructures leading to higher mechanical performance.
- Improved material utilization in forming small components due to productivity and accurate introduction of metal into the forming dies.
- Increased casting speed relative to liquid processing due to lower thermal demands on the dies.
- As substitute for sand casting, SSM cast parts production eliminates the environmental costs and problems of reclaiming and disposing of lead-contaminated sands.
- Allows for the lead content of red brasses to be much reduced and, combined with a semi-solid charge, should enable alloys normally prone to hot tearing to be die cast.

What is the SSM Casting Starting Material?

The starting stock for the SSM process must have the microstructure associated with low forming viscosity consisting of globular primary solid phase particles (i.e., non-dendritic) in a liquid matrix. Two important methods are utilized to produce the starting stock with this microstructure.

The first method is *Strain Induced Melt Activation (SIMA)*, where a cold worked bar is heated into the semi-solid state prior to forming. During heating, as the solidus temperature is approached, the structure recrystallizes to a fine equiaxed grain structure. As the solidus is exceeded, melting occurs at the grain boundaries to produce the SSM microstructure. A wide variety of alloys obtainable as extruded and cold drawn bar in the half-hard temper are suitable for this approach. To have sufficiently uniform cold work and recrystallization response, the bar size is limited to 1.5 inches (36 mm). A number of yellow brass alloys are readily available in this product form; others can be obtained as special orders. The SIMA method is simple and cost effective for certain parts production, demonstrated in the Parts Cost Analysis section. However, the parts must bear the premium for the extruded and cold drawn bar stock, making the process more expensive. Also, when multi-cavity dies are used, the small size of SIMA starting stock limits the economical application of the method to small parts with an allowance for the runner and biscuit.

Breakthrough in Extending Die Life for Copper Alloys

Pressure die casting is generally applicable only to relatively low melting metal alloys (e.g., aluminum, zinc and magnesium) because of severely limited die life experienced in die casting higher melting materials such as copper and its alloys. High die amortization costs have severely limited production of conventional as well as SSM die-cast copper alloy parts.

The recent development of the copper motor rotor has addressed the problem of extending die life. This project of the world copper industry, partially funded by a DOE NICE[3] grant and in collaboration with OTA, has solved the manufacturing problems associated with die casting pure copper by using a heated nickel-base alloy die system developed and demonstrated as the way to greatly extend die life over that of conventional die steels. The nickel-base alloys, INCONEL 617 and HAYNES 230, provide the high temperature mechanical properties and oxidation resistance required for handling copper and copper alloys. Operating the dies at high temperature (600 – 625℃) significantly delays the thermal fatigue failure mechanism, known as heat checking, by reducing the cyclic thermal and resulting strain gradients in the die. Motors with copper rotors are now in commercial production using this new die technology.

This high temperature die technology is now available for application to SSM casting of copper alloy parts. Because the melting range of the alloys is lower than that of pure copper, and because only about 50% of the heat of fusion will be transferred to the dies from the semi-solid charge, the die operating temperature to achieve good die life will be somewhat lower than that required for pure copper.

The second and more promising lower cost method to starting stock preparation is called *Slurry-at-the-Press*. Relatively inexpensive raw material, such as ingot or scrap, is melted in close proximity to the die casting machine and transferred to batch-sized stir crucibles for controlled cooling and stirring in a rotating magnetic field to form the appropriate SSM structure. The billets are induction heated to the forming temperature in the semi-solid state in a carousel assembly and transferred directly to the die casting machine and formed. An energy efficient variation to cooling and reheating the billets is to transfer the billets in the semi-solid state directly from the stirring step to the die casting machine. The Slurry-at-the-Press method eliminates the size limitation inherent to the SIMA method. Cost estimates indicate that slurry-at-the-press starting stock will cost about $0.15/lb over raw material cost, and is therefore considerably less expensive than the extruded and cold drawn bar starting stock of the SIMA method.

Parts Cost Analyses – SSM vs. Conventional Process

Two examples of sand-cast parts converted to SSM casting are shown here. Both cases show cost savings of approximately 40-50% over the conventional production method, even when the more expensive SIMA starting stock and conventional steel dies were used. The cost data presented here were obtained in the late-1980's, predating the concept of slurry-at-the-press starting stock. While material and operation costs may have changed, the cost savings realizable using SSM casting, expressed as a percentage of the conventionally produced part cost, are believed to be valid and probably conservative estimates for today.

Foundries today are under immense pressure to reduce the environmental impacts of their operations, including air emissions and the disposal of sand contaminated with metals and organic binders. Consequently, it is likely that today's cost of the parts as sand castings are higher when current environmental costs are included. On the other hand, SSM casting costs are free of these environmental costs. In addition, today's SSM casting costs benefit from the much improved die life using the heated nickel-base alloy die technology. An estimate of the additional savings attributable to the new die technology is included.

Split Bolt:
Sand Cast
This piece of electric utility pole line hardware (Figure 2) was traditionally sand cast for many years in copper alloy C95600, which is a silicon aluminum bronze with the nominal composition Cu–7 %Al–3%Si. At the time of this cost comparison, the finished part cost was $1.89 per piece including material, foundry, and machining costs.

SSM Cast
The part produced by SSM casting was made in the equivalent wrought alloy, C64200, purchased as cold drawn rod. The rod was cut into slugs of essentially the same part weight, 0.34 lbs. With the semi-solid tooling used, the entire billet was formed into the part with almost zero runner and biscuit to be removed. The process formed the part to final shape; no machining was required. The SSM cost breakdown was as follows:

Purchased Material	$0.68
Forming	0.33
Die Amortization	0.16
Total Costs	**$1.17**

Figure 2: Split Bolt Pole Line Hardware. C95600 Sand casting, left; SSM Formed in C64200, right.

This represents a 38% savings using the SSM casting process compared to sand casting. The die amortization cost could well be reduced by a factor of ten with the availability of the new die technology, which would increase the cost savings to 45%.

Water Pump Housing:
This pump housing (Figure 3) was sand cast in the semi-red brass casting alloy C84400, nominal composition Cu–3%Sn–9%Zn–7%Pb. The lead content assures pressure tightness and facilitates machining operations. The starting stock for SSM casting using the SIMA process was the yellow brass forging alloy C37700, Cu–38%Zn–2%Pb, purchased as readily available extruded and cold drawn rod. The wall thickness could be reduced because of the high density and absence of porosity that is characteristic of SSM-cast parts, resulting in a significant reduction in casting weight and material cost. In addition to the elimination of lead contaminated foundry sands, the lower lead content of the SSM-cast part also represents reduced contamination of the water through the pump.

	Sand Cast	*SSM Cast*
Weight As-Cast, lbs	1.66	0.87
Weight Machined, lbs	1.07	Not available

Cost Data	*Sand Cast*	*SSM Cast*
Cast Part, incl. Material	$3.03	n/a*
Purchased Material	n/a	$0.85
Forging	n/a	0.40
Machining/Finishing	2.45	1.20
Tooling	n/a	0.48
Total cost	$5.48	$2.93

* n/a = not applicable.

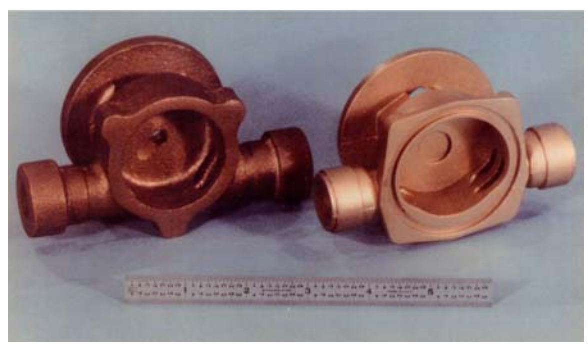

Figure 3: Water Pump Housing – C84400 Sand casting, left; SSM formed in C37700, right.

The cost saving here is 46% using SSM casting compared to sand casting. Again, longer die life by a factor of ten is expected and increases the cost saving to 54%.

Contacts

For more information or for discussion of potential cost savings using SSM casting of a particular copper alloy part, please contact:

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A more detailed description of SSM casting for copper alloys is presented in the technology transfer report "Copper Alloy SSM Casting: A Developing Technology for Reducing the Cost of Copper Alloy Parts," available at the OTA website (www.mass.gov/ota).

Vforge, Inc. is working with the Copper Development Association on copper alloy SSM process development, and offers production capability for SSM cast copper alloy parts. For more information, contact:

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